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L.F./M.F. RADIO-DATA: compatibility tests

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Research Department, Engineering Division
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SUMMARY

This report describes investigations which have been carried out to establish suitable parameters for an angle-modulation system for adding data signals to an m.f. or l.f. sound broadcast programme. Mechanisms causing crosstalk between data and sound channels in such a system are discussed and the likely degree of crosstalk is assessed. Suitable parameters for a data-signalling system are suggested, based upon results from a series of subjective tests made in the laboratory and over air.

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L.F./M.F. RADIO-DATA: COMPATIBILITY TESTS

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1. Introduction

A system for data-signalling on a radio broadcast channel simultaneously with normal sound programme must satisfy two major requirements. First, the data channel must be compatible with the existing sound service, which means that it must cause no significant impairment to the programme, and, second, it must be rugged enough to ensure a service area for the data which is at least as great as the service area for the associated sound programme. In addition the data-system should be designed for reception by low-cost receivers.

The ideal modulation system for the data channel is one that is orthogonal to the system used in the sound programme channel, (i.e. the parameter which is modulated in one channel should not be demodulated by elements in the other channel, either by chance or design). Unfortunately, the characteristics of practical receivers and transmitters and the nature of some propagation paths will make some degree of crosstalk between programme and data signals inevitable, despite any notional orthogonality.

The limited bandwidth available within a.m. sound broadcast channels imposes severe limits upon the choice of a modulation system for an additional data signalling channel. The existing a.m. channel bandwidth and spacing prohibits the use of ultrasonic subcarriers, as is possible on v.h.f. f.m. transmissions[1]. Two alternatives remain which would require only simple demodulation in a receiver; these are to use a sub-audio subcarrier on the a.m. channel or to use angle-modulation of the carrier. Angle-modulation is preferable to the use of a sub-audio a.m. subcarrier because existing transmitters could be easily converted, whereas there is doubt as to the suitability of many transmitter amplitude-modulating stages for handling sub-audio tones. For this reason it was decided, from the outset, to discard the use of a sub-audio subcarrier and to concentrate upon the use of angle-modulation.

This report describes investigations into crosstalk between an angle-modulated data-channel and the amplitude-modulated programme channel and the determination of suitable modulation parameters for a compatible data signalling system. Other work, including extensive field trials to discover the degree of compatibility in practice and the probable service area of a system using the proposed parameters, is described in a companion report[2].

2. Factors affecting the choice of modulation parameters of an L.F./M.F. Radio-data signalling system

2.1. General

Having decided that angle-modulation was the most suitable for a data signalling system on L.F. and M.F., it was necessary to decide whether to use phase-modulation (p.m.) or frequency-modulation (f.m.). This choice depended upon both the relative degree of programme impairment that each might introduce and their relative ruggedness as data transmission systems.

The essential difference between p.m. and f.m.[3] is that, with p.m. the instantaneous phase of the carrier varies proportionally with the modulating signal, whereas with f.m. the instantaneous phase of the carrier varies with the integral of the input signal. Thus the two systems will produce different r.f. spectra from the same input signal and, for a given value of peak phase-deviation, the spectrum of a phase-modulated signal will have more high-frequency sideband components[4] than a frequency-modulated signal. For systems with a low peak phase-deviation (in the order of 90° or less), phase-modulation has a considerable noise advantage over frequency-modulation[4, 5, 6]. However, the advantage lies with f.m. for high-deviation systems so the choice between p.m. and f.m. depends on the value of deviation which is finally chosen.

There are two main parameters in an angle-modulation system which may be varied to affect the degree of crosstalk into the a.m. sound channel. These are the peak phase-deviation and the data-rate. (The form of filtering and secondary coding used for the data signal is, of course, relevant but it can be assumed that the baseband spectrum-width of the data signals would be kept to a minimum in practice.)

The process of crosstalk from angle-modulation to amplitude-modulation is referred to as phase-modulation to amplitude-modulation conversion (p.m./a.m. conversion). The reverse process is referred to as a.m./p.m. conversion. There will be mechanisms causing a.m./p.m. and p.m./a.m. conversion throughout the signal path shared by data and sound channels. As shown in Fig. 1, crosstalk can occur at the transmitter, within the receiver or along the transmission path. The following sections discuss briefly the mechanisms which will cause crosstalk.

In this report there is some discussion of a.m./p.m. conversion, as it will effect the ruggedness of a data-system using angle-modulation. In a practical system, it is important that the phase-deviation used for the data signal is significantly greater than the spurious phase-deviation caused by a.m./p.m. conversion (within the data-signalling bandwidth).

Obviously if the maximum amount of phase-deviation allowable on the basis of compatibility is insufficient to give the required ruggedness, the system would not be viable.

2.2. The generation of crosstalk in transmitters and receivers

Crosstalk in transmitters and receivers can be generated by both linear and non-linear mechanisms. Non-linear circuits such as transmitter output stages and r.f. mixers are likely to produce a.m./p.m. conversion due to device impedances changing with drive level. Another, more indirect, cause of a.m./p.m. conversion in receivers can be the frequency-modulation of the local-oscillator and the variation of junction capacitances in the r.f. and i.f. stages due to the audio programme output signal modulating the power supply voltage in conventional receivers. The severity of these effects will depend greatly upon the particular circuit design but, as it is the data signal which suffers, such effects can be minimised when designing data receivers.

Frequency-selective circuits such as aerial matching networks and receiver filters can produce both a.m./p.m. conversion and p.m./a.m. conversion

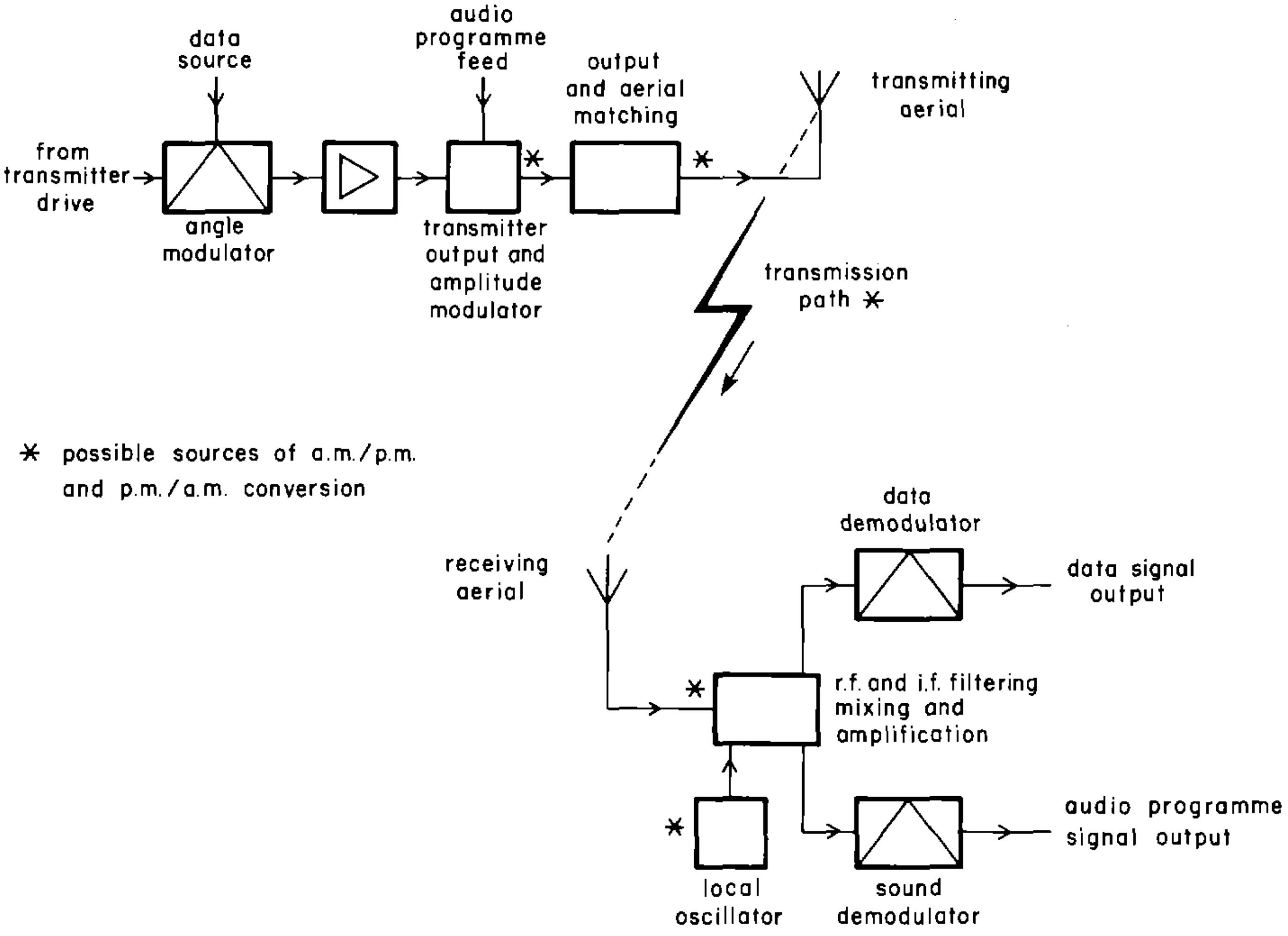
data source
audio programme feed
output and aerial matching
transmitting aerial
from transmitter drive
angle modulator
transmitter output and amplitude modulator
transmission path *
* possible sources of a.m./p.m. and p.m./a.m. conversion
receiving aerial
data demodulator
data signal output
r.f. and i.f. filtering mixing and amplification
audio programme signal output
local oscillator
sound demodulator

Fig. 1—Schematic diagram of a radio-broadcast chain.

if their amplitude/frequency response is asymmetrical about the carrier (or i.f.) frequency. Group delay distortion will also cause crosstalk. Appendix 1 describes more fully the generation of crosstalk in filters.

The results of the experiments described in Section 3 suggest that the limits imposed on the signalling parameters are not, in fact, due to mechanisms within transmitters or receivers but are predominantly due to transmission path effects at the edges of the transmitter service area.

2.3. The generation of crosstalk on the transmission path

When, in addition to the wanted signal, an interfering carrier of the same frequency is received, both p.m./a.m. and a.m./p.m. conversion can occur, in addition to the well-known effects of fading and "beating". The interfering carrier may be present under any of the following three conditions:

1. Co-channel interference – where the interfering carrier is on nominally the same frequency and carries a different audio programme.

2. Mush-area interference – where two or more, possibly phase-synchronised, carriers are received from a group of transmitters each of which carries the same audio programme.

3. Sky-wave interference – where ionospheric propagation conditions allow a sky-wave and ground-wave from the same transmitter to interfere with each other.

Each of the three forms of interference imposes its own limitations on the normal service area of a transmitter (in the absence of data signalling). Criteria have been drawn up in the past which define the limits of a.m. service areas in terms of levels of the different types of interference[7].

In assessing the compatibility of the proposed data-signalling system, the levels of interfering carrier used in the tests were those which define the edge of the usable a.m. service area. Additional impairment to the received signal due to crosstalk from the data-signals in nominally "unserved" areas has been disregarded. However, as the criteria used for the subjective tests described in this Report were very stringent, it is unlikely that many areas with even remotely acceptable a.m. services would be noticeably affected by data signals using the parameters proposed.

Appendix 2 deals more fully with the effects of the above kinds of interference. It can be seen that the degree of crosstalk from the data signal modulation depends upon the mean phase between the wanted and interfering carriers. In both sky-wave fading areas and mush areas, the worst effects of crosstalk occur over only a limited range. Under these conditions of relative phases, where the interfering carriers are near cancellation, the accompanying impairments of programme distortion and high noise will tend to mask the impairments of the programme due to crosstalk. Both forms of impairment will vary in degree over the standing-wave interference pattern of the two carriers. This standing-wave pattern may drift over the service area, or, when the transmitters are mean-phase synchronised, will remain stationary.

3. Experimental investigations

3.1. General

A number of laboratory and over-air experiments were carried out to determine the dominant mechanisms in the a.m. sound broadcast chain which might limit the compatibility of data signalling using angle-modulation. As a result of the experiments, possible parameter values emerged.

In the experiments, the mechanisms discussed in Section 2 were examined and these involved the subjective assessment, by a number of observers, of impairment to sound programme quality. Where possible, the experiments attempted to examine effects singly but, in the case of the over-air tests described, this was not possible and any impairment heard by listeners could, of course, be caused by more than one mechanism.

It is important, in such an investigation, to make the tests in the appropriate order, so as to avoid the effects of one mechanism in the signal path masking the effects of another mechanism. The tests were carried out as follows:

First, high-quality laboratory modulators were used to produce a.m. and p.m. of an m.f. carrier with appropriate programme and data signals respectively. This ideal signal was fed to a number of typical domestic receivers and subjective measurements were made to find values of the angle-modulation parameters which produced acceptably low impairments to the sound programme. Having done this, it was then possible to use domestic receivers to examine the effects of p.m./a.m. conversion in transmitters.

This was done in over-air subjective tests using a typical m.f. broadcast transmitter. Unfortunately, as the severity of the effects was unpredictable, the tests had to be conducted at night, outside normal programme hours. Despite other U.K. co-channel stations having been switched off, there remained a certain amount of interference from foreign stations which affected some of the results, even within the nominal ground-wave service area. Nevertheless, the results indicated that the parameter values were unlikely to be limited by the characteristics of normal m.f. transmitters.

Laboratory simulations were next carried out to discover the subjective impairments due to sky-wave fading, mush-area distortion and co-channel interference. Again an ideal signal was used and the impairments were assessed subjectively by a number of listeners using domestic receivers. It was found that the effects of sky-wave interference would dominate the choice of values of the modulation parameters. The tests are described in more detail in the following section.

3.2. Receiver tests

In the laboratory, an "ideal" received signal was produced using a good quality amplitude-modulator and a linear, wideband amplifier. Fig. 2 shows the experimental set-up for test-signal generation. The m.f. carrier input to the amplitude-modulator was frequency- or phase-modulated with bi-phase†[5] data signals using various data-rates and phase-deviations. The programme signal consisted of speech, with pauses, and piano music. In a quiet listening-room, the impairments introduced by

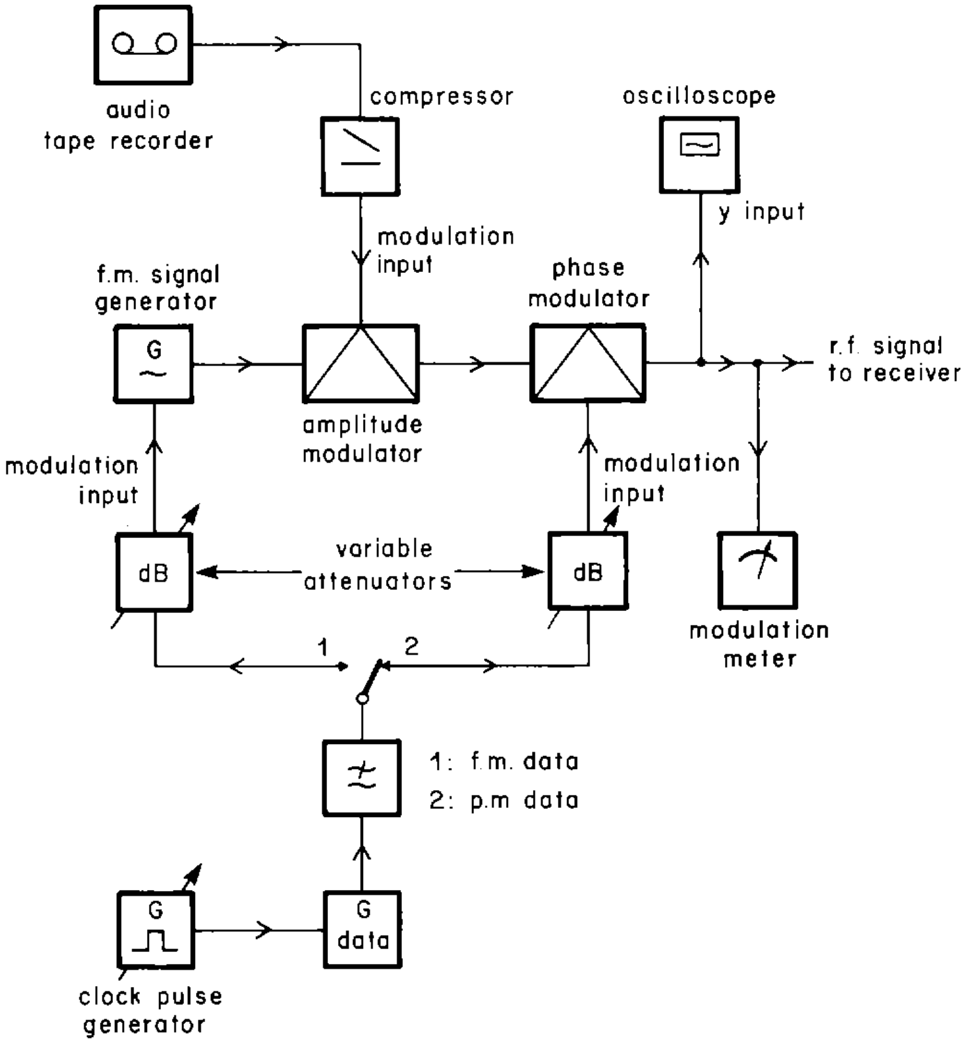

Fig. 2—Experimental signal-generation for receiver tests.

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† Biphase L or Manchester Biphase.

a.m./p.m. conversion in a number of domestic receivers were assessed subjectively by a number of experienced subjects. The receivers were deliberately mis-tuned to produce worst-case impairment and the deviation by the data signal was progressively reduced for each subject until the impairment was, firstly Grade 4‡ (Perceptible but not annoying) in the presence of programme and then Grade 5‡ (Imperceptible). The latter assessment was, of course, highly pessimistic but gives a lower limit to the permissible deviation. Figures 3, 4, 5 and 6 show the results of the tests for two representative domestic a.m. receivers, one a battery-portable and one mains-powered "Hi-Fi" with its output fed to a high quality monitoring loudspeaker. The extended low-frequency response of the monitoring loudspeaker accounts for the greater apparent sensitivity of the mains-powered receiver to the low-frequency angle-modulation. The graphs show both receivers to be more sensitive to phase-modulation than to frequency-modulation at the data-rates used. This, however, is partly due to the fact that the ratio of peak-to-mean phase-deviation is higher for frequency-modulation than for phase-modulation. Moreover, for a given error-rate in the data-channel, the peak phase-deviation in a low-deviation f.m. system would need to be greater than for phase-modulation and so the impairment to the sound signal caused by both systems would be similar.

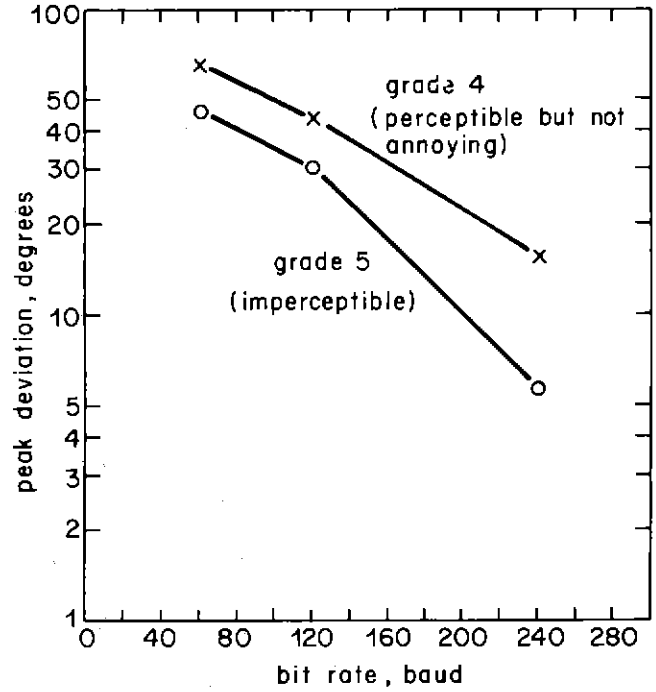

Fig. 3—Variation of peak deviation with bit rate for a given impairment grade, using phase-modulation. (Receiver 1 (Battery Portable))

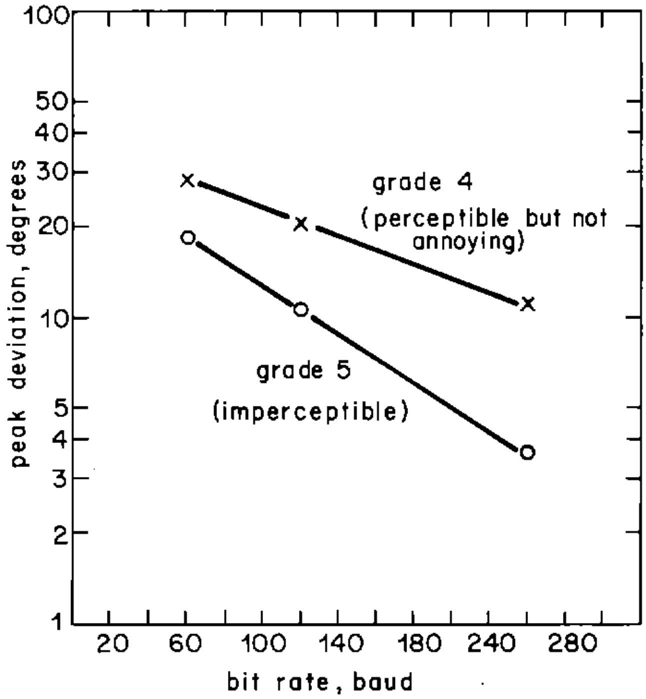

Fig. 4—Variation of peak deviation with bit rate for a given impairment grade, using phase-modulation. (Receiver 2 (Mains Powered "Hi Fi"))

As mentioned before, the results quoted are extremely pessimistic, assessment being made for worst-case mis-tuning. To produce the worst-case impairment required care and, in general with receivers tuned for reception of the audio programme in the absence of data signals, much higher values of phase-deviation could be tolerated (higher by a factor of at least ten) before the impairments were assessed to be the same as for the worst-case results. Still further increases in deviation were possible if the receivers were tuned to reject the impairment (it was noted that tuning for minimum impairment also produced optimum sound quality in all cases).

The graphs of the test results imply that, for example, with a data-rate of 100 bauds, an impairment grade of 4 (perceptible but not annoying) can be achieved with a peak-deviation of 23° using p.m. and 110° using f.m. However, as discussed above, these values of deviation could be increased considerably in practice.

3.3. Transmitter tests

The transmitter test-transmissions were broadcast during the night, after normal closedown, from

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‡ CCIR 5-point Subjective Impairment Scale.

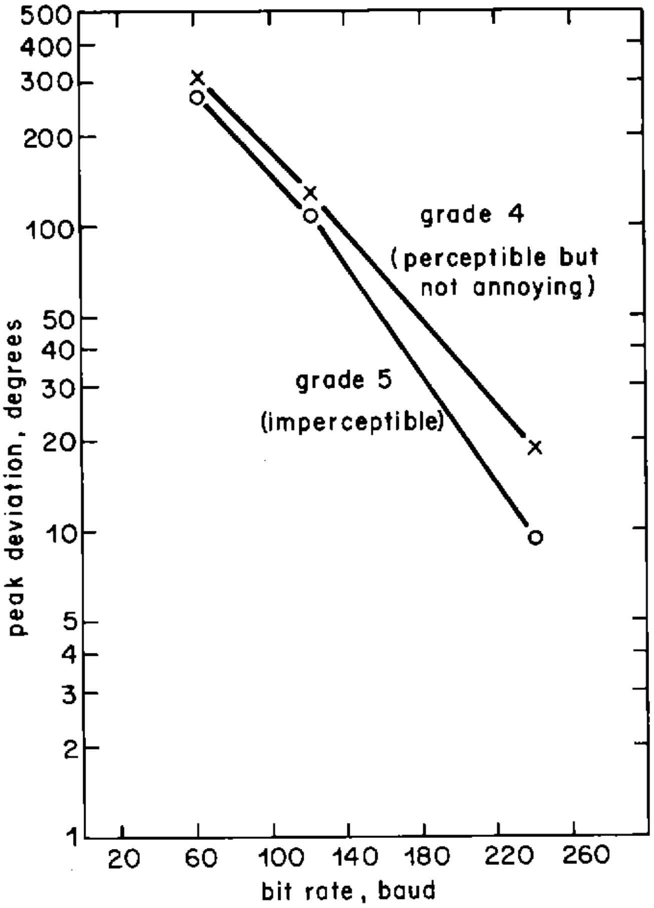

Fig. 5—Variation of peak-deviation with data-rate for a given impairment grade, using frequency-modulation. (Receiver 1 (Battery Portable))

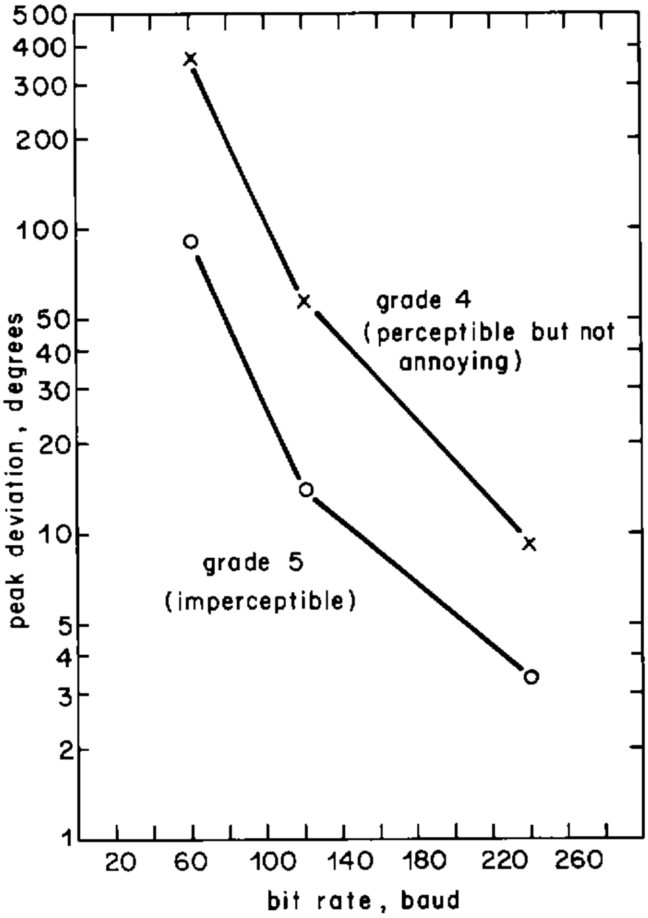

Fig. 6—Variation of peak-deviation with data-rate for a given impairment grade, using frequency-modulation. (Receiver 2 (Mains Powered "Hi Fi"))

an m.f. transmitter at Brookmans Park.

Data transmissions were made using both phase- and frequency-modulation with a range of data rates and deviations. The values of the parameters used for the tests were chosen in the light of the laboratory test results. The values of deviation used were between 22½° pk and 90° pk and the data rates were from 60 bauds to 240 bauds.

The data signals were transmitted in the presence of an audio programme signal which was, in this case, some piano music with pauses.

About forty volunteer subjects listened on domestic receivers in their own homes and assessed the subjective impairments caused by the data signals, using the CCIR 5-point impairment scale. Part of the test involved the listeners' tuning their receivers to minimise or eliminate impairments and to comment upon this procedure.

The majority of receiving sites were well within the nominal ground-wave service area of the transmitter. With no other synchronous transmissions taking place, the only mechanisms expected to produce impairments due to data signalling would have been within the transmitter or the receiver. However, the received co-channel sky-wave foreign interference was at a high level and many of the subjects complained of excessive impairments throughout the test due to this cause.

The results of the tests were somewhat disappointing from a scientific point of view because few, if any, of the listeners either heard any impairment attributable to the data signal modulation or graded the impairment in a way which correlated with the parameters used. Even deliberate mistuning of receivers was not found to produce significant audible impairments related to the data signals. The few instances where impairment was reported as due to data signal modulation could possibly be attributed to sky-wave fading or fluctuating interference from a weak co-channel station with a very low beat-frequency; this effect was discussed in Section 2.3.

Whilst it would have been possible to re-run the over-air tests using increased angle-modulation parameters in order to find maximum permissible values, this was not considered worthwhile in the light of the results of the tests described in Section 3.4.

It was concluded that no significant impairments are likely to be generated by transmitters or receivers using the highest phase deviations likely to be chosen.

3.4. Transmission path simulation

As already mentioned, the transmission-path compatibility tests were conducted using laboratory simulations. It was necessary to simulate the sky-wave tests because of the unpredictable behaviour of the ionosphere and obvious experimental difficulties. The initial mush-area tests were also simulated in the laboratory because over-air tests could not be run in the daytime because of a risk of impairing the received programme for the public. Moreover tests could not be run during the night because of possible sky-wave interference which would confuse the results.

3.4.1. Sky-wave simulation

Sky-wave simulation tests were carried out using equipment described in references 8 and 9. The basic experimental arrangement is shown in Fig. 7 and the equipment works, briefly, as follows. A simulated broadcast signal with phase-modulated data signals was produced at 850 kHz. This signal was split into two paths, one direct (representing the ground-wave signal) and one passing through a switched magneto-strictive delay line (thereby introducing the delay to which the sky-wave signal is normally subjected). The sky-wave signal was split into three further paths and all four signals were frequency-changed to 950 kHz using four 100 kHz unsynchronised crystal-oscillators. The combination of the three delayed signals in appropriate proportion produced a delayed carrier varying in phase and amplitude in much the same way as a typical sky-wave signal. Combining this with the simulated ground-wave signal and adjusting amplitudes appropriately, produced a signal with a fading depth of 10 dB, which corresponds to the nominal, maximum acceptable value.[7] By altering the fine tuning

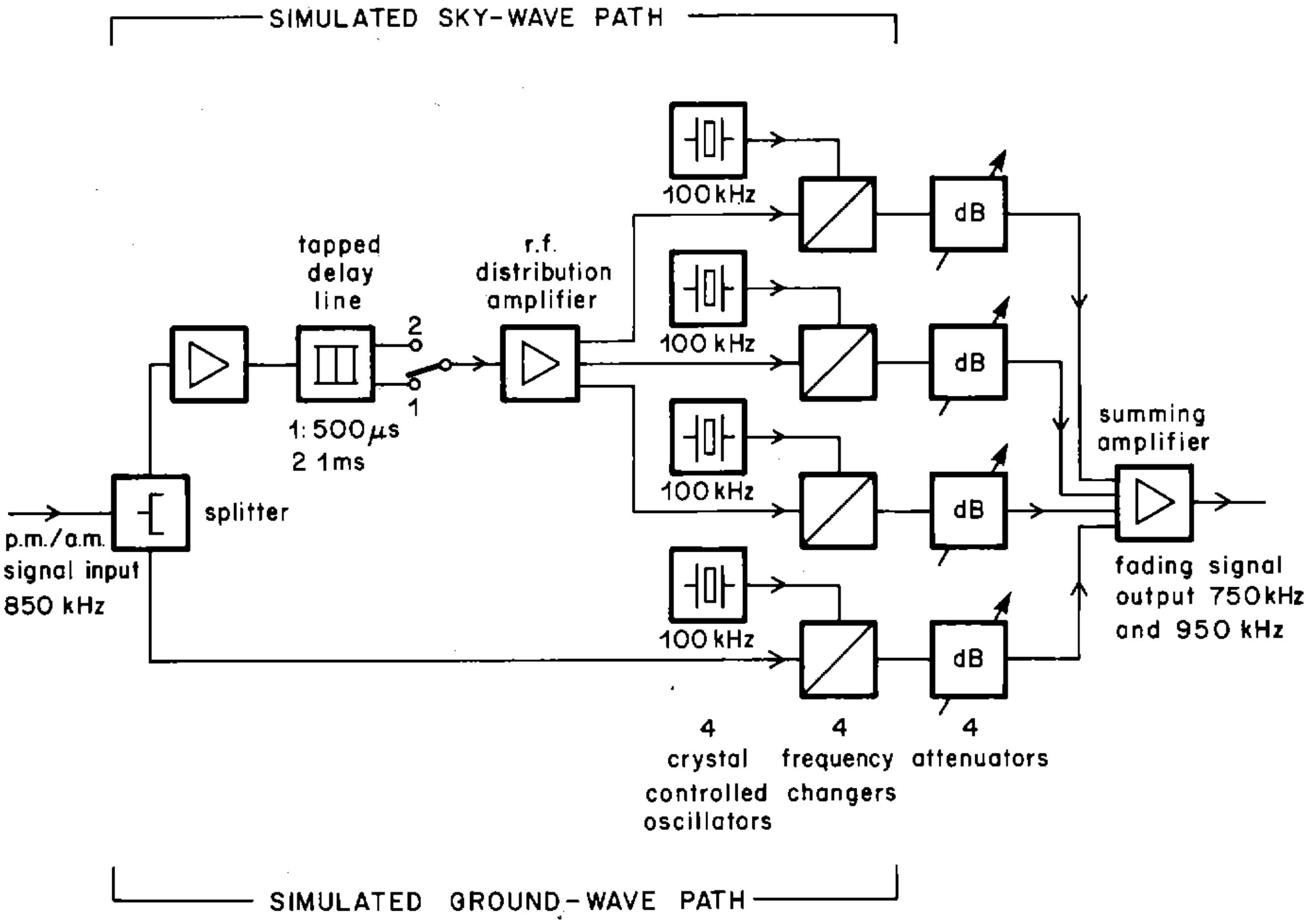
SIMULATED SKY-WAVE PATH
tapped delay line
r.f. distribution amplifier
2
1
1: 500μs
2 1ms
splitter
p.m./a.m. signal input 850 kHz
100 kHz
100 kHz
100 kHz
100 kHz
dB
dB
dB
dB
summing amplifier
fading signal output 750kHz and 950 kHz
4 crystal controlled oscillators
4 frequency changers
4 attenuators
SIMULATED GROUND-WAVE PATH

Fig. 7—Schematic diagram of the Sky-wave fading simulator.

of the crystal oscillators, the fading cycle time was adjusted to about 2 s. Two values of delay (500 μs and 1 ms) were used for the sky-wave path.

Subjective tests were carried out in a quiet listening room, using typical domestic receivers, as in the previous tests. Eight experienced subjects were asked to grade the impairments caused at the worst parts of the fading cycle for various phase-deviations and data-rates. The programme used for the tests consisted of male and female speech with pauses. The range of phase-deviations used was between $11\frac{1}{4}^\circ$ peak and $22\frac{1}{2}^\circ$ peak and the range of data-rates used was between 20 baud and 80 baud. As expected, (see Section 7.3) the worst impairment due to the data signal occurred before and after the point where partial carrier-cancellation caused the worst distortion to the programme. Hence, although the overall poor quality of the received programme under sky-wave fading conditions could have affected subjective judgements, the impairment caused by the data signals was only partially masked by the more common fading distortions.

Fig. 8 shows the results of the subjective tests using a mains-operated receiver with its output fed to a high quality monitoring loudspeaker. Of all the receivers, the relatively good low-frequency a.f. response of this receiver and loudspeaker made it the most sensitive to impairments due to sky-wave interference. The results can thus be regarded as somewhat pessimistic and it is unlikely that any other receiver would reveal significantly worse impairments due to sky-wave interference.

The results indicate that, if the impairment due to data signalling is to be imperceptible when sky-wave interference causes a fading range of 10 dB, then, for a relative delay of up to 1 ms between the ground wave and sky-wave signals, the data rate must not exceed 50 bauds for a phase deviation of $11\frac{1}{4}^\circ$ pk.†

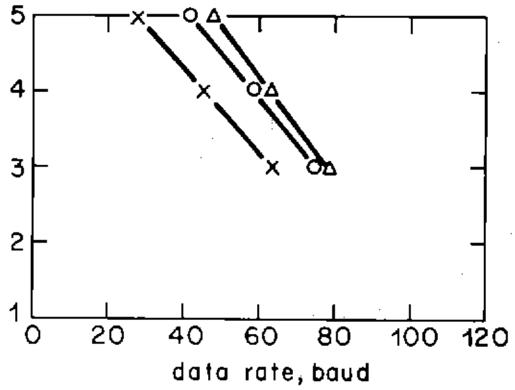

Fig. 8—Relationship between data-rate and subjective impairment grade under limiting sky-wave interference conditions for a range of peak-deviation values.

× ——— × $22\frac{1}{2}^\circ$ peak deviation
○ ——— ○ 15° peak deviation
△ ——— △ $11\frac{1}{4}^\circ$ peak deviation

3.4.2. Mush-area simulation

A full simulation of mush-area reception[10] with phase-modulation data signalling on both received carrier signals was not possible because only one phase-modulator was available for the tests. It was possible, however, to simulate normal mush-area reception of an amplitude-modulation signal and to introduce impairments equivalent to those likely to be caused by data signalling in a mush area.

The experimental arrangement is shown in Fig. 9. The output of an m.f. signal-generator was split into two paths, representing signals from two phase-synchronised m.f. transmitters. In each path was an amplitude-modulator and a variable attenuator. An audio programme signal was fed to both amplitude-modulators, a switched audio delay-line being introduced into one path to simulate mis-timing of the two audio modulations at a receiving point in a mush area. A variable r.f. phase shifter in one of the r.f. paths was used to bring the carriers into a near anti-phase condition and the two variable attenuators provided control of the ratio of the two carrier amplitudes before recombination. In one leg of the r.f. path was a phase-modulator, modulated with low audio-frequency tone. The deviation using the a.f. tone can be related to the relative phase-modulation between two received signals due to mis-timing (as discussed in Section 7.2 of the Appendix). The deviation of the modulation was adjusted using an attenuator. The resulting output signal was listened to on a mains-operated m.f. receiver with a good-quality monitoring loudspeaker.

The impairment resulting from the recombined signals, one with and one without phase-modulation, was assessed for various mean-phase differences around the antiphase condition. For the low values of phase deviation proposed for data signalling as a result of the sky-wave interference tests, no significant inaccuracy was introduced by using this approximate method. Six experienced subjects took part in the listening tests and they were asked to vary

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† The sky-wave limited service area for l.f. transmissions is greater than for m.f. transmissions and the height at which the sky-wave is reflected by the ionosphere is less. The resulting path difference between sky and ground waves will be correspondingly less, giving a smaller relative delay. It should therefore, be acceptable, in the case of l.f. data signalling to increase the deviation for a given baud rate.

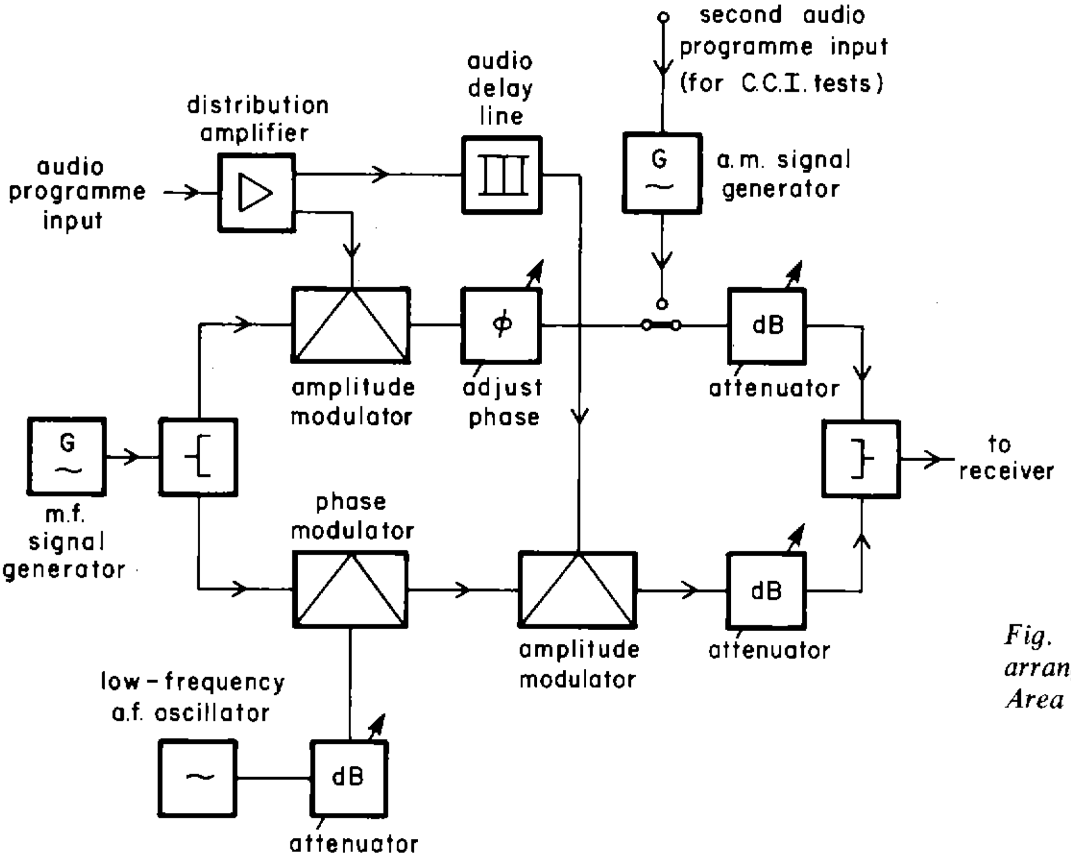

Fig. 9—Experimental arrangement for Mush-Area and CCI simulation

the setting of the attenuator on the input to the phase-modulator until they judged the impairment to be Grade 4 (Perceptible but not annoying). The assessments were made for various values of carrier ratio and various frequencies of phase-modulation.

Table 1 shows the results of the tests for carrier ratios ranging from 0 dB to 3 dB. The values of relative phase-deviation shown are mean values for a number of subjects. These values can be related to possible combinations of timing accuracy and relative phase-deviation for data signal modulation. The right hand columns of the table show examples of such combinations. The column showing the timing accuracy required for a phase-deviation of 11¼° peak is included in the light of the sky-wave tests described in Section 3.4.1. The signalling frequency used was 25 Hz (corresponding to a 50 baud data signalling rate).

The results are somewhat pessimistic for various reasons – firstly, because of inadequacies in the audio modulation-delay equalisation, it is probably that in most areas with received carrier

Table 1 Results of the Mush-Area simulation tests
(25 Hz tone modulation was used to represent a data signal with a data rate of 50 baud)

Test Results		Implications of the results		
			Required timing accuracy	
Carrier Ratio dB	Maximum relative peak phase-deviation for Grade-4† Impairment	Peak signalling deviation for ±40 μs timing accuracy	For 45° pk deviation	For 11¼° pk deviation
0	0.57°	45°	±40 μs	160 μs
1	1.33°	105°	±95 μs	380 μs
2	2.67°	280°	±190 μs	760 μs
3	4.51°	356°	±320 μs	1300 μs

† Perceptible but not annoying.

ratios of less than 2 or 3 dB the existing impairments would mask those due to data-signalling.[†] Secondly, the assessments were made for carrier phase conditions which exist for less than five per cent of locations or time. Thirdly, sinusoidal phase modulation causes the worst level of impairment possible. The impairment due to practical data signals will be less when data remains unchanged for more than one bit period – the relative deviation during such events being near-zero.

3.4.3. Co-channel simulation

During the mush-area interference laboratory tests, the subjects were asked to assess the impairment due to data signal modulation under simulated conditions of co-channel interference at a maximum acceptable level. This was simulated by injecting a different audio signal into the amplitude modulator of the second r.f. path shown in Figure 9 and reducing the relative level in this path to -30 dB relative to the wanted signal.

The overwhelming opinion of the subjects was that whatever the offset frequency of the interfering carrier and, hence, whatever the frequency of the audible inter-carrier beat, the addition of phase-modulation to the wanted carrier had no effect whatsoever upon the effective level of impairment.

4. Conclusions

Work has been carried out to investigate the mechanisms which determine the maximum deviation and data rate for a data-signalling system which is to be compatible with l.f./m.f. sound broadcasts.

The work has revealed that, of all mechanisms likely to cause crosstalk from an angle-modulated data channel into an amplitude-modulated sound channel, the dominant effect is that of sky-wave interference. The fact that there is no practical way of independently controlling the times of arrival of data signals carried by ground and sky-waves determines that, for a data signalling rate of 50 baud, the maximum permissible phase-deviation is $\pm 11\frac{1}{4}^{\circ}$ pk-pk. Use of such a low value of peak deviation favours phase rather than frequency-modulation due to its greater ruggedness.

Using the modulation parameters proposed, crosstalk caused within either the transmitter or receiver circuitry is insignificant. In addition, the effects of mush-area distortion during the daytime may be reduced to an insignificant level by synchronising the arrival times of the data signals to within 160 μs.

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6. Appendix I
The generation of crosstalk in frequency-selective circuits

Crosstalk will occur whenever the relative phases or amplitudes of the sideband components of an amplitude- or phase-modulated signal are disturbed.

Fig. 10a shows how a.m./p.m. conversion will occur when the upper and lower sidebands of an a.m. signal differ in amplitude (as, for instance, in a mis-tuned receiver). Phasor notation is used to show the carrier and sidebands present in sinusoidal a.m. As the sideband vectors rotate with respect to the carrier, the resultant (r) will vary in phase (θ) relative to the carrier, as shown.

Fig. 10b shows the effect of asymmetrical filtering on a phase-modulated signal. The first order sidebands resulting from sinusoidal p.m. are shown

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[†] Later work[2], involving day-time over-air listening tests in a Mush Area has confirmed that the presence of other forms of programme impairments effectively masks any distortions due to data mis-timing of the order of 0.5 ms when using the above signalling parameters.

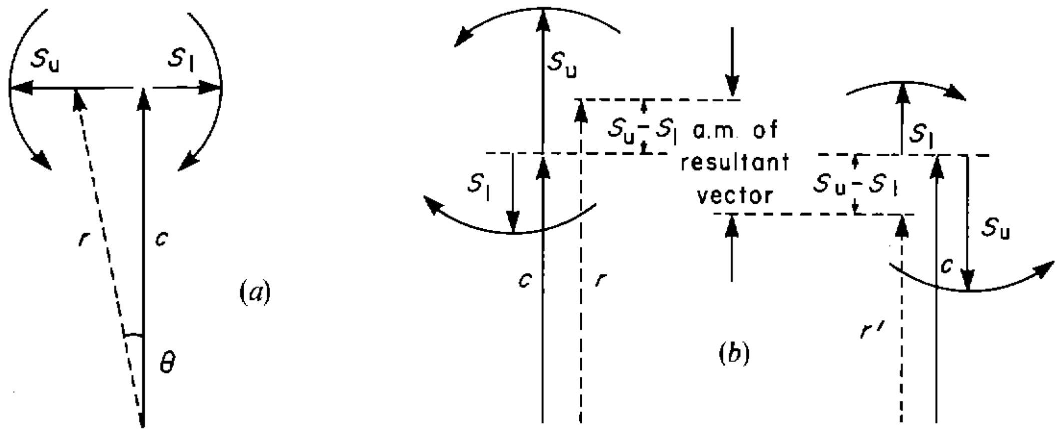

Fig. 10—The generation of crosstalk due to assymetry in amplitude/frequency response.
(a) a.m./p.m. conversion (b) p.m./a.m. conversion

c = carrier vector
S_u, S_l = Upper and lower sideband vectors
r, r' = Resultant vectors produced at different times in the modulation cycle.

in two stages of phase rotation with respect to the carrier. Because of the unequal amplitudes of the sidebands, the resulting vector r will vary in magnitude between the extremes shown. (Higher order sidebands have been omitted for clarity.)

An indication of the degree of crosstalk which may be expected due to asymmetry in amplitude/frequency response can be gained from the following examples. A difference of 1 dB between upper and lower sideband amplitudes with a depth of modulation of 90 % will produce phase-modulation with a peak deviation of about 5°, whilst a 3 dB difference will produce about 17° peak deviation.

When a phase-modulated carrier with a peak deviation of 1 radian is passed through an asymmetrical filter with 1 dB of difference in gain between upper and lower first-order sidebands, amplitude modulation of 6.5 % will be produced. If the difference is 3 dB, the resultant carried will have 19 % amplitude-modulation.

Group-delay distortion in frequency-selective circuits will also produce crosstalk by disturbing the phase relationship between spectral components. Fig. 11a shows two a.m. sidebands which, due to group-delay distortion, produce a resultant vector which is out of phase with the carrier vector. The phase angle (ϕ) between the overall resultant (r) and the carrier vector will vary over the modulation cycle, producing a.m./p.m. conversion. The amount of a.m./p.m. conversion can be severe for high levels of modulation depth. For instance, with 90 % a.m., if the carrier phase is just 1° different from the phase of the resultant of the two sidebands the overall resultant will have a peak phase modulation of 4.5° introduced.

Fig. 11b shows the effect of group-delay distortion on a phase-modulated carrier. Vectors s_1 and s_2 represent, respectively, the instantaneous sums of the quadrature and in-phase sideband components. These vectors vary in amplitude over the modulation cycle to produce a resultant (r) of constant magnitude which follows the arc PP′ between the peaks of deviation. The effect of group delay distortion will be to alter the phases (and possibly the amplitudes) of the vectors s_1 and s_2 to those of s'_1 and s'_2, for instance. The resultant (r') of these new components will have a different magnitude and phase. The difference will vary over the modulation cycle and will correspond to distortion of the p.m. signal and p.m./a.m. conversion.

If the phase modulation has a peak deviation of 1 radian then disturbing the sideband resultants by 1° with respect to the carrier will produce about 1 % a.m.

7. Appendix 2
The generation of crosstalk by R.F. carrier interference

Fig. 12 shows how crosstalk can occur in the presence of an interfering carrier.

Conversion from a.m. to p.m. is shown in Fig. 12a where an amplitude-modulated carrier (C_w) is shown interfering with an unmodulated carrier (C_i). The two resultant vectors r and r' which are pro-

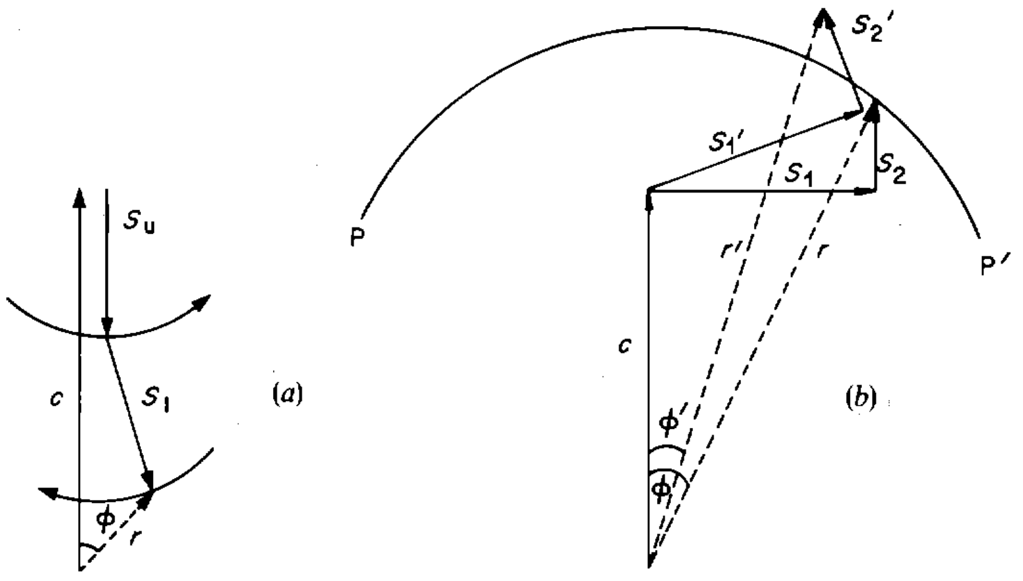

Fig. 11—The generation of crosstalk due to group-delay distortion.
(a) a.m./p.m. conversion (b) p.m./a.m. conversion

c = Carrier vector
Su, S_l = Upper and lower sideband vectors
S_1, S_1' = Vector sum of in-phase sideband components
S_2, S_2' = Vector sum of quadrature sideband components
r, r' = Resultant vector produced at different times in the modulation cycle.
ϕ, ϕ' = Phase-modulation angle.

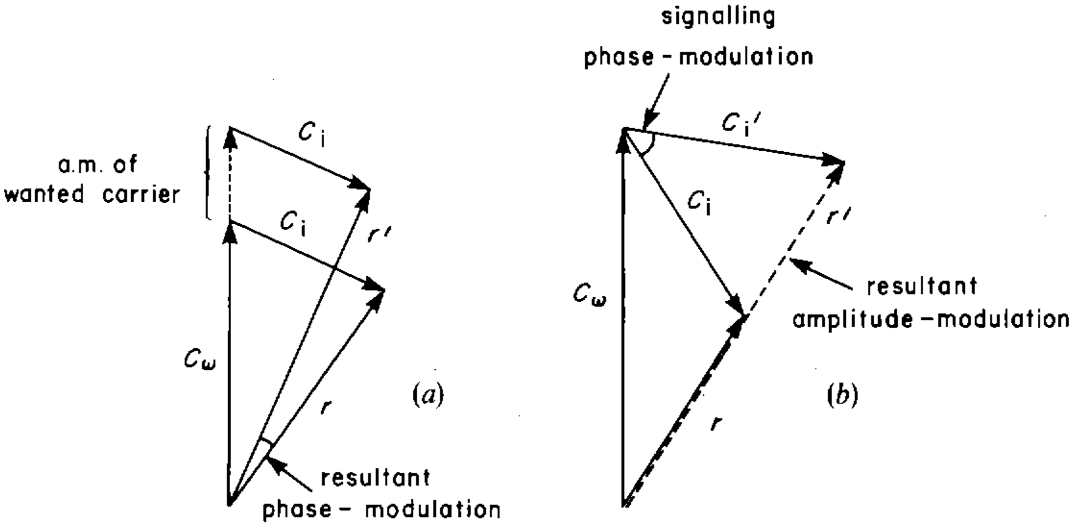

Fig. 12—The generation of crosstalk by the addition of an interfering carrier wave.
(a) a.m./p.m. conversion (b) p.m./a.m. conversion

C_w = Wanted carrier vector
C_i, C_i' = Interfering carrier vector
r, r' = Resultant vectors produced at different times in the modulation cycle

duced at different times of the amplitude-modulation cycle of C_w can be seen to have different amplitudes and phases.

Conversion from p.m. to a.m. is shown in Fig. 12b, where a carrier (C_w) is shown interfering with another carrier (C_i) which is varying in phase relative to C_w. The two extremes of phase variation are shown by C_i and C_i'. The resultant will vary in amplitude between the extremes shown by vectors r and r'.

If the frequencies of C_w and C_i are different, then C_i will rotate about C_w at the difference frequency, producing a "beat" whether or not the carriers are modulated.

7.1. Co-channel interference

If the wanted and interfering carriers are carrying unrelated programme then the maximum level of interfering carrier for acceptable reception is −30 dB relative to the wanted carrier.[7] Under this condition there will be breakthrough of the unwanted programme at up to −30 dB and a phase-modulated data signal can produce a.m. to a maximum depth of 6 %. This is also the level of the whistle generated by the beat between the two carriers. With data signalling, the impairment will tend to be a "burble" rather than a whistle.

Interference to the wanted phase-modulation will occur when an interfering a.m. carrier has a component in quadrature with the wanted carrier, and will be greatest when a peak of interfering carrier modulation coincides with a trough in the wanted carrier modulation. When the wanted carrier is amplitude-modulated at 100% then, for a short time during each cycle of programme modulation, the unwanted phase deviation can be as much as 90° peak; however, the r.m.s. deviation will be small.

7.2. Mush-area interference

When two a.m. transmitters on the same carrier frequency radiate the same sound programme, acceptable reception is possible in those areas (referred to as mush-areas) where signals from both transmitters are received, provided that the ratio of the received carrier levels is not less than 10 dB.[7] By using appropriate timings for the audio inputs to the transmitters, the two received modulations can be made synchronous at a point where the received field strengths are equal; this technique is known as modulation-delay-equalisation. The required accuracy of synchronisation is ±30 μs or 30°, whichever is the lesser, at a given modulating frequency.[10] This procedure makes reception acceptable during the daytime over the major part of the mush-area, including some locations where the received field strengths are equal. (At night, due to sky-wave propagation, the mush-area may be subject to interference which cannot be reduced by the above methods.)

When the received carriers are almost equal in amplitude, p.m.–a.m. conversion will be severe for certain mean carrier-phase-differences (see Fig. 12a). If the phase-modulation were confined to only one of the two transmissions then for example with a peak deviation of only 10° and a carrier ratio of 3 dB the amplitude-modulation could be as high as about 23 %. The mechanism is discussed more fully in 7.4.

When both transmissions carry identical data-signal phase-modulation then, at an arbitrary receiving point within the mush-area, the times of arrival of the two data signal modulations may be different. Fig. 13 shows an example of the phases of two such carriers. The varying component of the phase between the two carriers can be regarded as an effective deviation of one carrier. It approximates to the product of the relative time-delay between the signals, the peak phase-deviation and the speed of the transitions of the data signal, (for relative delays much less than one data period). For a given value of effective deviation there will, consequently, be a tradeoff between these 3 quantities.

The amplitude-modulation depth due to p.m./a.m. conversion has been calculated (see Section 7.4) for various carrier ratios and effective deviations and plotted against mean phase-difference between carriers. Figs. 14, 15 and 16 show that the most severe p.m./a.m. conversion at low carrier-ratios occurs near, but not at, partial cancellation. (A maximum occurs on both sides of the antiphase condition). The horizontal dashed lines on each curve show the level of a.m. which is exceeded at 5 % of locations at a given time (or 5 % of the time at a given location). If the two transmitters have carrier mean-phase synchronism, however, then the impairment will remain at the same level in a given location, whilst if the carriers are not synchronised then the impairment will vary in time.

By synchronising the arrival times of the data signals with sufficient accuracy, the impairments produced by p.m./a.m. conversion can be reduced to an insignificant level in any areas where the sound programme would be acceptable on its own. It is difficult to predict the subjective impairment due to p.m./a.m. conversion of the data signals in the presence of a received programme which is already impaired by mush-area distortion. Inadequacies in the programme modulation-delay equalisation (dis-

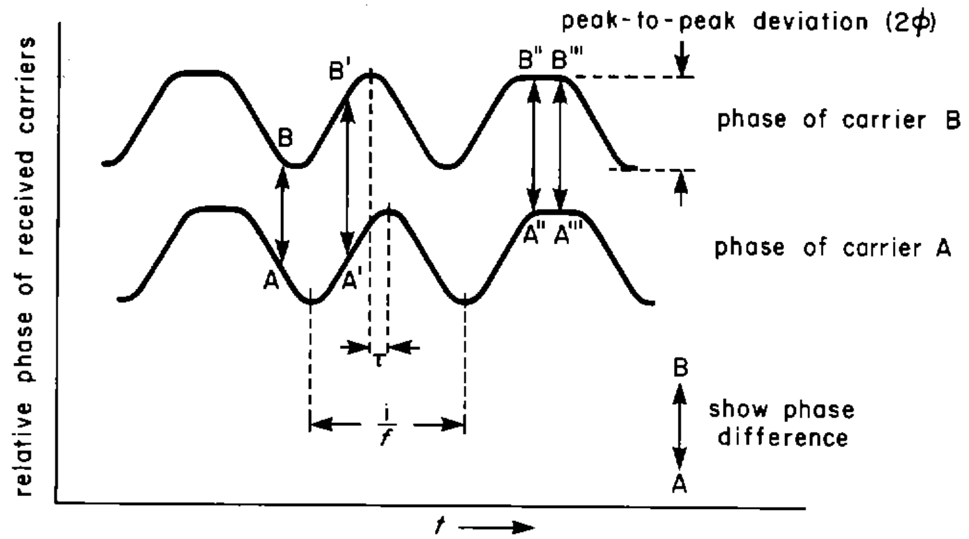

Fig. 13 - Variation of phase-difference between two received carriers due to mis-timing of arrival of data-signals.

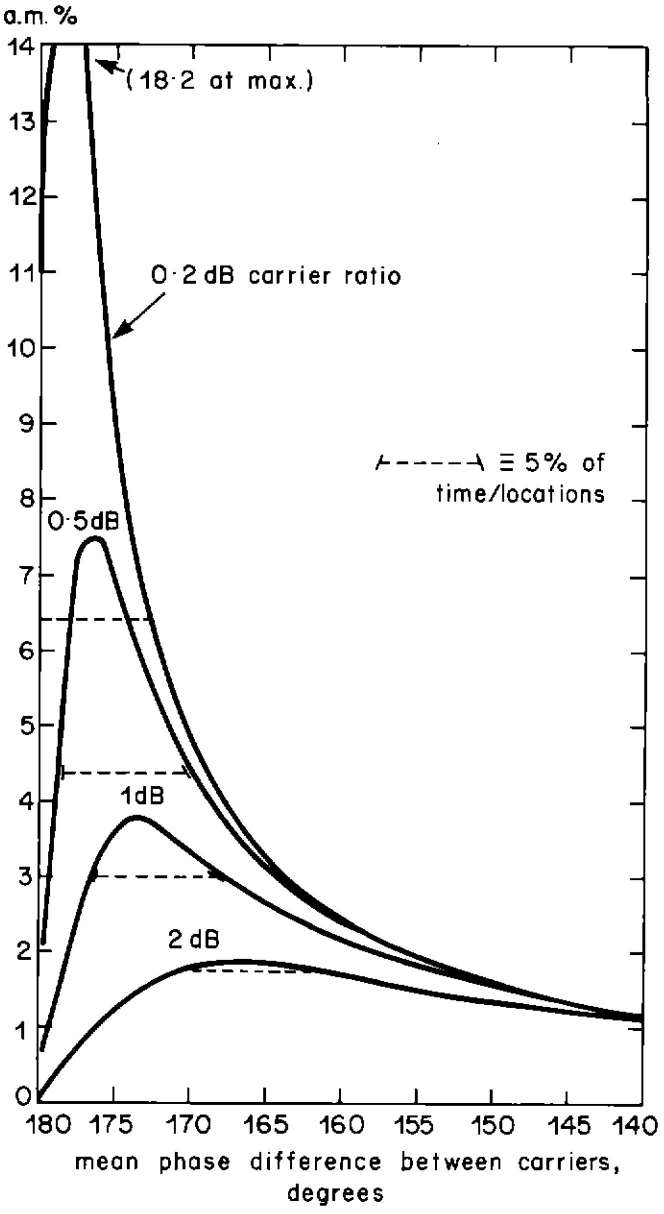

Fig. 14—p.m./a.m. conversion caused by two carriers interfering. (Relative phase deviation = 0.5° pk).

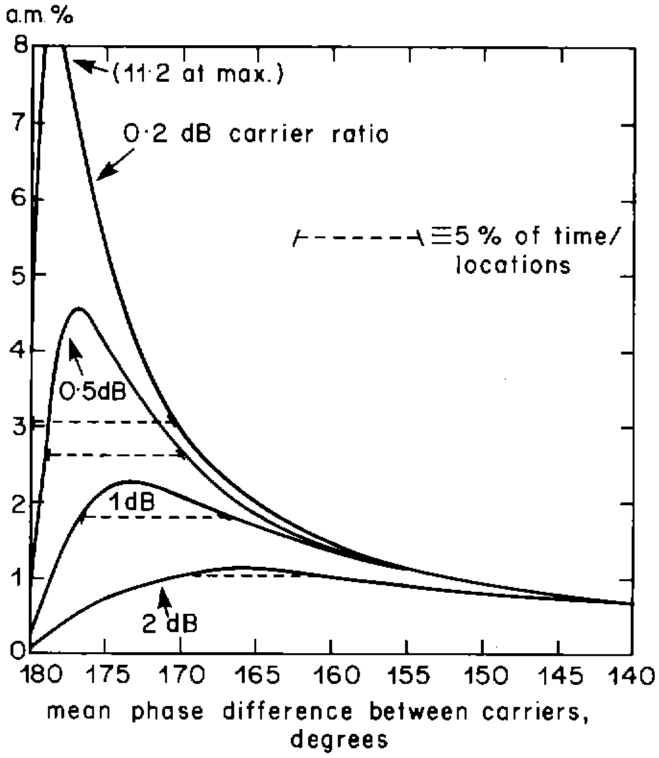

Fig. 15—p.m./a.m. conversion caused by two carriers interfering. (Relative phase deviation = 0.3° pk).

persion and timing errors in the programme feed) limit the effectiveness in areas of near-equal field strengths, and in many parts of the mush-area the additional impairment caused by data signalling is likely to be masked to some extent.

Section 3.4 in the main part of this report discusses subjective tests which were conducted to discover the required accuracy of synchronism.

7.3. Sky-wave interference

In an area subject to sky-wave interference, the

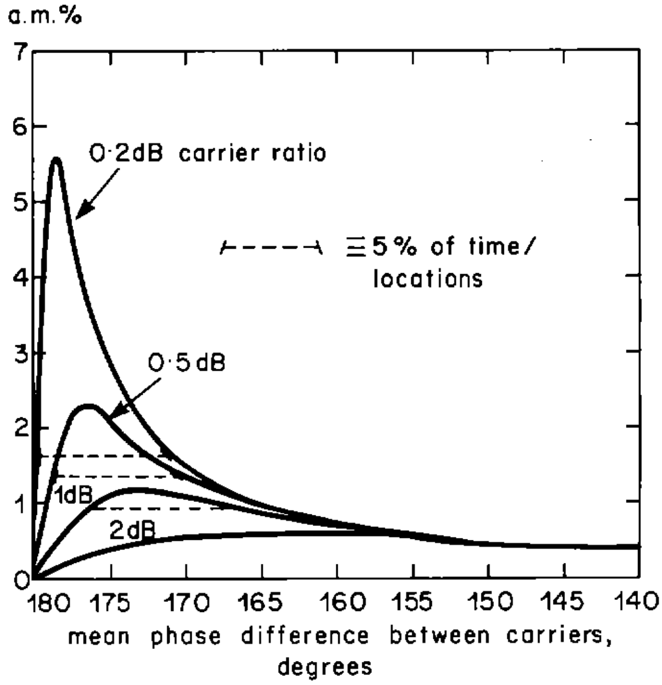

Fig. 16—p.m./a.m. conversion caused by two carriers interfering. (Relative phase deviation = 0.15^c pk.)

same problems exist as in a mush-area. In this case, however, there is no opportunity for synchronising the times of arrival of the signals carried by the ground and sky-waves. The difference in arrival times is set by the difference in lengths of the two transmission paths. Depending on the carrier frequency, the time of day and the distance between transmitter and receiver the relative delay can be in the region of 0.2 ms to 1 ms. Impairments to the audio programme without data signalling are such that satisfactory sound reception is not possible where the ratio of received carriers is less than 6 dB (this condition gives about 10 dB of fading depth).[7]

In practice, the ionospheric layers are continually moving and the relative mean phase between ground and sky-waves continually alters over a period of several seconds. As in a mush-area, the maximum impairment due to p.m./a.m. conversion occurs not during the antiphase condition, but on either side of it. The impairment due to p.m./a.m. conversion is not, therefore, totally masked by the peak in distortion and noise occurring during the antiphase condition. Figure 17 shows how the degree of p.m./a.m. conversion varies with the phase

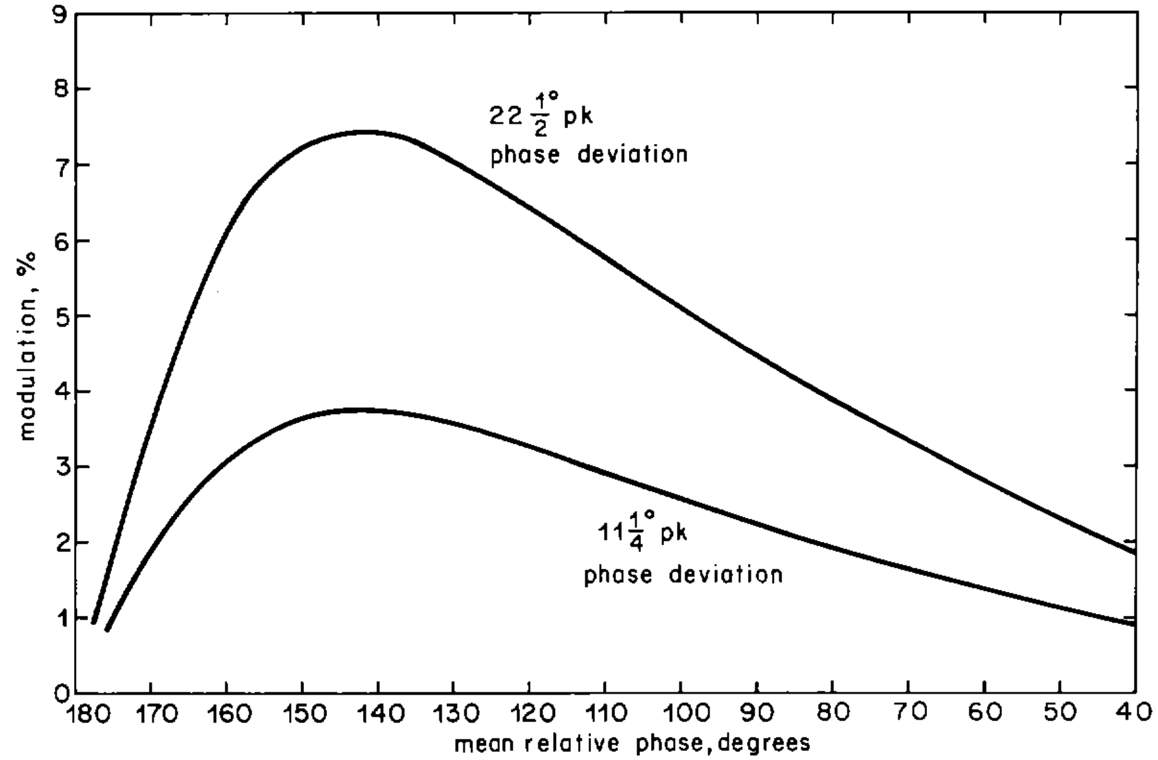

Fig. 17—Expected levels of p.m.–a.m. conversion due to sky-wave interference, shown for two values of carrier phase deviation. (0.9 ms relative delay, 25 Hz phase-modulation frequency, skyway interference at −6 dB relative to ground-wave signal)

angle between the two received carriers. The values on the graph are derived by the method described in Section 7.4. The peaks on the two curves shown are considerably broader than those for the p.m./a.m. conversion in a mush-area (Figs. 14, 15 and 16) where the carriers are more nearly equal but with less effective phase-deviation between them. It can be expected that the subjective impairment due to a given level of crosstalk will be worse during sky-wave fading since it exists for a greater proportion of time (or locations) than in a mush-area.

7.4. Conversion from p.m. to a.m. in mush-areas and areas with sky-wave interference

In both mush-areas and sky-wave interference areas, two carriers are received, each modulated with the same sound programme and each carrying the same data signals. If the received data signals arrive with a time difference τ and the highest data frequency (corresponding to alternate ones and zeros) is f, then the amplitude of the varying component of phase between the two carriers will be ϕ where:

$$\phi = \theta[\sin(2\pi f t) - \sin\{2\pi f(t - \tau)\}] \quad \ldots(1)$$

where θ is the peak phase deviation of the data signalling and the transitions between states are sinusoidal. (In practice the data waveform may not have sinusoidal transitions, but this simplified treatment will not introduce any significant error.)

This may be re-written:

$$\phi = 2\theta \cos\left[2\pi f\left(t - \frac{\tau}{2}\right)\right]\sin(2\pi f\tau/2) \quad \ldots(2)$$

Equation 2 has a maximum value of $2\theta\sin(\pi f\tau)$ at time $t = \tau/2$.

A range of values of θ and τ will yield the same value of ϕ for any given value of f. In the case of mush-area reception, τ may be chosen by the broadcaster to be any value over a limited portion of the mush-area[10].

If the value of τ is less than one half-bit period then, for a data stream containing two or more sequential ones or zeros the maximum value of θ will occur only during transition in phase. ϕ will be zero when there are no transitions. (See A″–B″ and A‴–B‴ in Fig. 13.)

For the purpose of calculating p.m. to a.m. conversion using low values of peak phase deviation, it is sufficient to represent the received wanted carrier as a fixed vector and the interfering carrier as a vector with a mean phase of $\bar{\psi}$ relative to the wanted carrier, and an effective deviation equal to ϕ, the varying component of the relative phase between the carriers. (Other mechanisms causing p.m./a.m. conversion of a single carrier have already been discussed and their effects may be neglected here.)

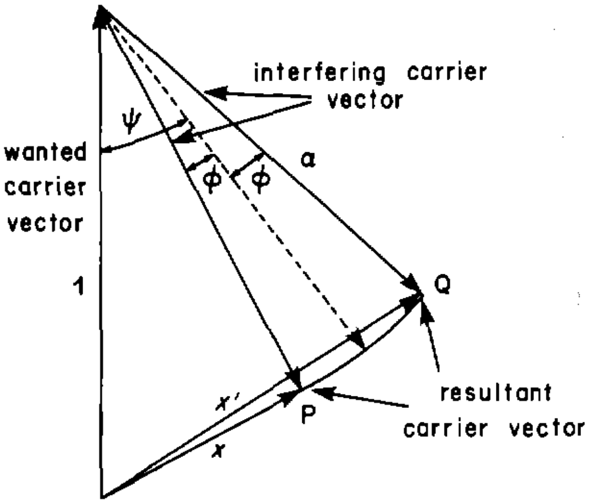

Fig. 18—The addition of received carrier vectors in Mush or Sky-wave fading areas.

$\bar{\psi}$ = Mean phase difference
ϕ = Peak phase-deviation

In Fig. 18 the two received carrier vectors are shown. It is assumed that there is no programme modulation. The wanted carrier, of unit amplitude, is shown stationary and the interfering carrier, of amplitude a, is shown at its mean phase $\bar{\psi}$ and two extremes of phase ($\bar{\psi} - \phi$ and $\bar{\psi} + \phi$).

The resultant vector will follow the arc PQ as the phase between the carriers varies. Its amplitude and phase will vary over the signalling cycle, maximum and minimum values being x' and x. By inspection of the figure it can be seen that the peak phase deviation of the resultant carrier can never exceed $\pi/2$, whatever the values of ϕ or a and, for the values of signalling parameters likely to be used, no appreciable p.m./a.m. conversion should result within receivers due to phase modulation of this resultant carrier.

Between the two values x' and x, the carrier amplitude will vary monotonically with ϕ (except when the arc PQ crosses the axis of the wanted carrier vector, in which case the calculations may be done separately for positive and negative values of ϕ). The depth of amplitude modulation may be calculated as follows:

Values of $|x|$ and $|x'|$ can be found using the cosine rule

$$|x| = [1 + a^2 - 2a\cos(\bar{\psi} - \phi)]^{1/2} \quad \ldots(3)$$

$$|x'| = [1 + a^2 - 2a\cos(\bar{\psi} + \phi)]^{1/2} \quad \ldots(4)$$

The amplitude of the resultant is not a linear function of the effective deviation; nevertheless, the depth of amplitude modulation may be calculated from:

$$m = \frac{|x'| - |x|}{|x'| + |x|}$$

Figs. 14, 15, 16 and 17 show the resultant a.m. index for a range of carrier amplitude ratios $(1/a)$ and effective deviations.

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